A Reassessment of the Satellite Record of Glacier Change in the Rwenzori Mountains, East Africa

ANDREW G. KLEIN[1] AND JONI L. KINCAID[2]

ABSTRACT

Three massifs in Eastern Africa currently have glaciers. Glaciers in two of these, Mt. Kenya and Mt. Kilimanjaro, have received extensive study. The third, the Rwenzori Mountains on the border of Uganda and the Democratic Republic of the Congo has been the focus of less research, but some recent studies have been undertaken. Glaciers on all three massifs have been shrinking in recent decades. A recently published study has examined glacier retreat in the Rwenzori from 1987 to 2003 using Landsat satellite images. Our analysis of the images used in this study, however, reveals that the 1995 and 2003 images contain significant snow outside of the glaciers and therefore are unreliable indicators of glacier extent. Using a combination of Landsat, ASTER and SPOT images of the Rwenzori glaciers, ice areas have been reevaluated for the period 1987 to 2006. The Normalized Difference Snow Index (NDSI) and visual mapping were used to determine the glacier areas. Our analysis indicates that the glaciers in the Rwenzori have decreased in area from 2.55 km^2 in 1987 to 1.31 km^2 in 2006. These areas, like previous estimates, are not without their own uncertainties.

Keywords: Remote Sensing, Glaciers, Tropics, Africa

INTRODUCTION

There are currently three massifs that support glaciers in Africa. Two of these ranges, Kibo on Kilimanjaro and Mt. Kenya have been the site of exhaustive studies. The third, the Rwenzori Range, which lies on the border of the Democratic Republic of the Congo and Uganda (Figure 1) has received much less study though some work has recently been published (Kaser and Osmaston, 2002; Mölg et al., 2003; Taylor et al., 2006). However, despite recent work, the measured glacier retreat, as well as the interpretation of the climatic factors responsible for the retreat since the 1980s remains controversial.

Recently, Taylor *et al.* (2006) published a glacier retreat time series for the Rwenzori Range of Eastern Africa based on analysis of Landsat Thematic Mapper images and published estimates of glacier extent from field observations (Kaser and Osmaston, 2002). To extract glacier extent from Landsat images in their study Taylor *et al.* (2006) used both a supervised classification and the Normalized Difference Snow Index (NDSI). Based on their analysis, Taylor et al. (2006) assert that glaciers in the Rwenzori have experienced a constant retreat rate since 1905 when the first mapping of the glaciers was undertaken.

[1] Department of Geography, MS 3147, Texas A&M University, College Station, TX 77853-3147, tel: 979 845-5219, email: klein@geog.tamu.edu
[2] Department of Geography, MS 3147, Texas A&M University, College Station, TX 77853-3147, tel: 512-431-9963, email: jkincaid@geog.tamu.edu

Taylor *et al.* (2006) attributed the measured ice loss to increasing air temperatures without significant changes in precipitation. The climatic interpretation, and to a lesser degree, the glacier mapping has been challenged (Molg et al., 2006). Taylor et al. (2006) responded to the criticisms, especially on the climatic interpretation, but did not address in detail the problems with the satellite derived time series of glacier retreat.

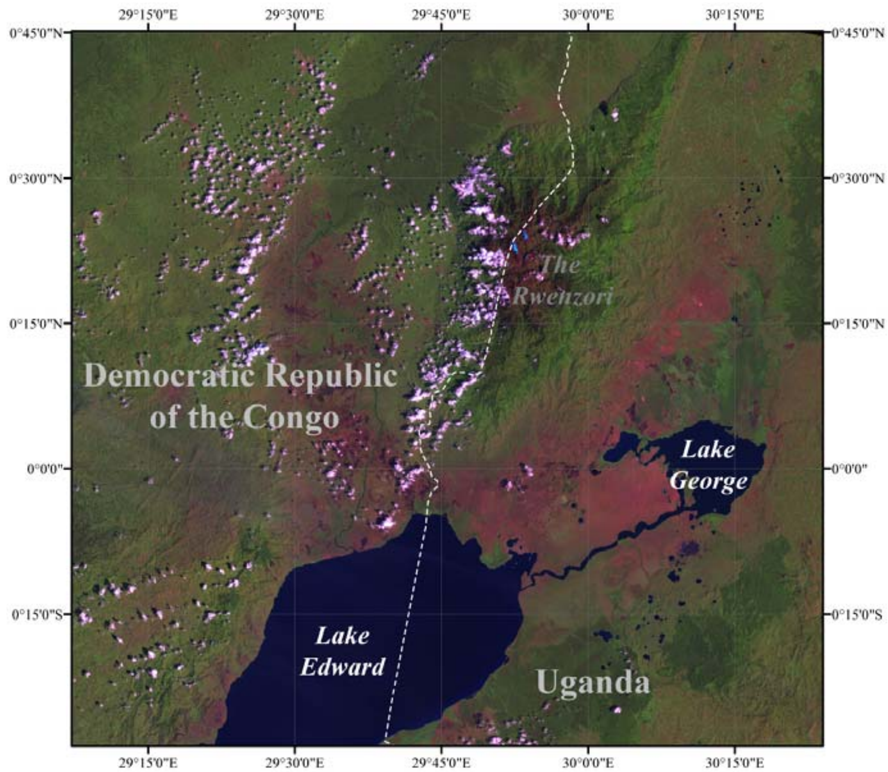

Figure 1. 1987 Landsat TM image (bands 542) of the Rwenzori Mountain Range, showing the three currently glaciated peaks of Mount Stanley, Mount Speke and Mount Baker.

In this study, we provide an extended analysis of the satellite image record that highlights inaccuracies of previous analysis. While discussion of the climate interpretations drawn from their analysis is beyond the scope of this research, this work provides an alternative analysis of the satellite image record of glacier change in the Rwenzori. We believe our time series to be a more accurate depiction than that in Taylor et al. (2006) of the actual changes in snow and glacier cover captured in the satellite record.

STUDY AREA AND PREVIOUS GLACIER MAPPINGS

Glaciers in the Rwenzori range are currently confined to three peaks in the range: Mt. Stanley, Mt. Speke and Mt. Baker (Figure 2). The highest altitude of these peaks is in excess of 4800 m with Mt. Stanley exceeding 5000 m. (Mt. Stanley: 5111 m, Mt. Speke: 4891 m and Mt. Baker: 4873 m). Published estimates of glacier extent based on field observations are limited to three times: 1906, 1955, and 1990. These glacier areas are presented, as revised by Kaser and Osmaston (2002) in Table 1. The glacier extents for these dates are illustrated in Figure 3. In 1990, glaciers in the Rwenzori extended from approximately 4400 m to over 5000 m. A thorough discussion of the Rwenzori and its glaciers can be found in Kaser and Osmaston (2002).

Table 1. Glacier areas (km^2) in the Rwenzori (Table 6.6.1 from Kaser and Osmaston, 2002).

Peak	1906	1955	1990
Mt. Baker	1.47	0.62	0.12
Mt. Speke	2.18	1.31	0.56
Mt. Stanley	2.85	1.88	1.00
Total	6.51	3.18	1.67

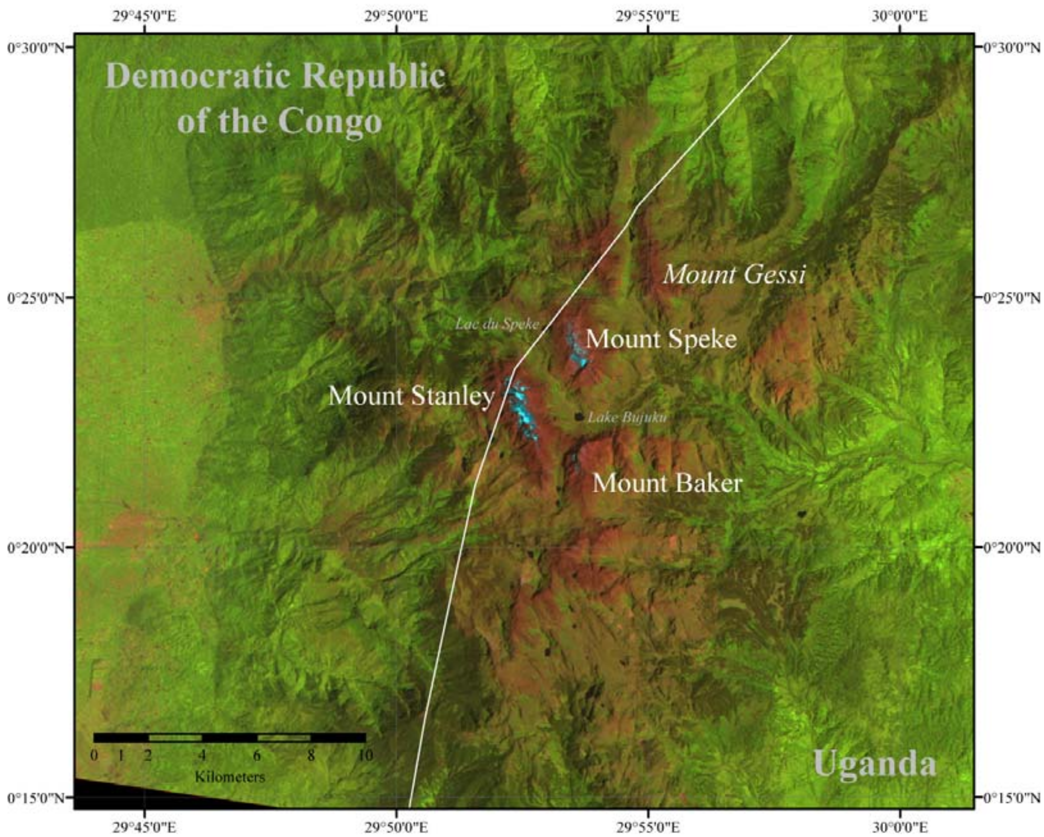

Figure 2. An ASTER false color composite image (bands 4, 3 and 2) of the Rwenzori showing the three currently glacierized massifs: Mt. Stanley, Mt. Speke and Mt. Baker.

METHODS

Glacier extents were mapped using the NDSI method as well as through visual mapping. Linear spectral unmixing was also attempted, but problems caused by shadowing made the technique less reliable than the other two methods in determining glacier extent.

Several major limitations exist to using remote sensing to map glacier retreat in the Rwenzori. Due to persistent cloud cover the image archive is quite limited and the limited series of images selected for analysis is illustrated in Figure 4. It is evident from Figure 4, that several dates, most notably those in 1995 and 2003, are impacted by transient snow cover.

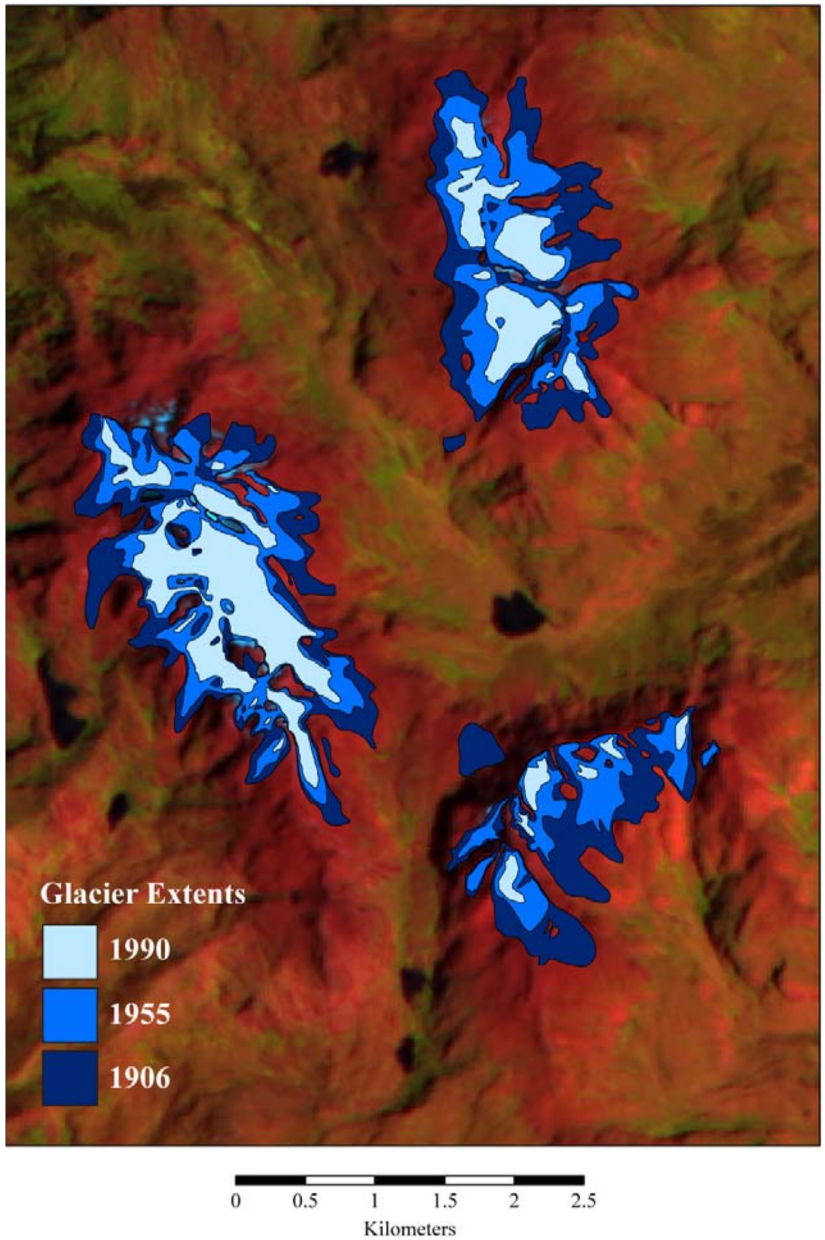

Figure 3. Mapped glacier extents of the Rwenzori for 1906, 1955 and 1990 from Kaser and Osmaston (2002) overlain on an ASTER false color composite (bands 4, 3 and 2) from 2005.

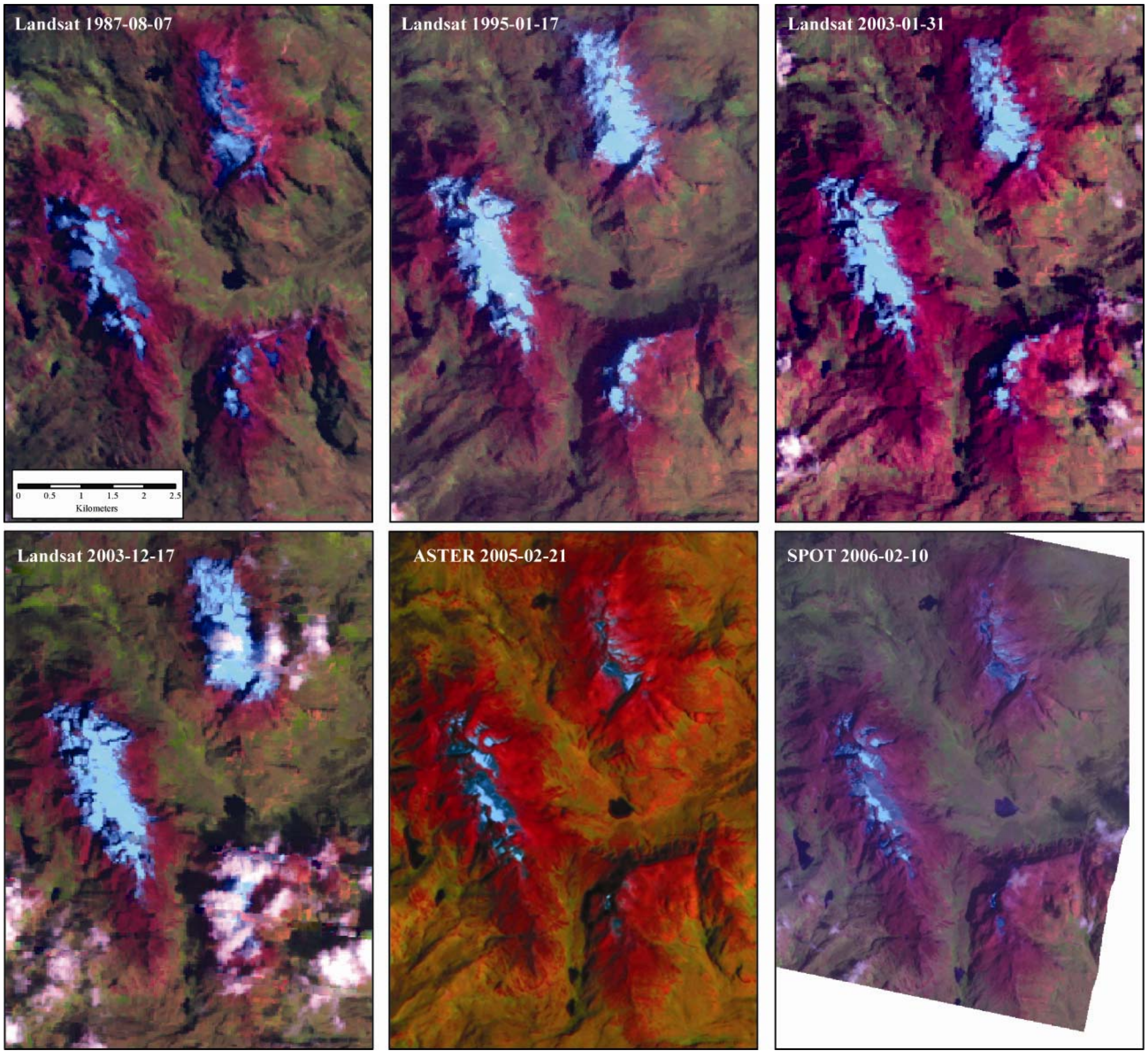

Figure 4. False color composites of all images selected for analysis. Each false color composite is composed of a mid-infrared band (red), a near-infrared band (green) and a visible band (blue).

Image Processing

All Landsat, ASTER and SPOT scenes used in this study were processed in a similar manner to assure as comparable glacier mapping results as possible using the applied mapping techniques.

Geometric Rectification

To facilitate comparisons between images, all images were geolocated. Initially, all Landsat and the 2005 ASTER image were coregistered using a polynomial warp to the ASTER image. Subsequently, this original geometric rectification, an improved digital elevation model and the ASTER and Landsat images were shifted several tens of pixels in the Y direction to bring them into better alignment with the Digital Elevation Model (DEM). To bring the SPOT image into alignment with the other images it was necessary to orthorectify the image. Orthorectification was accomplished using the ENVI 4.3 image processing software along with the DEM and ground control points selected from the 2005 ASTER image.

Radiometric Preprocessing

For all image types, the original DN (digital numbers) values were converted to at-satellite radiances (W m^{-2} sr^{-1} μm^{-1}). This was accomplished using the gains and offsets provided by the data providers. For ASTER images, this step was accomplished using the automated procedures provided by ENVI 4.3 while for Landsat and SPOT the gains and offsets were individually input for each sensor and band.

The radiance values were then converted to at-satellite reflectance using the general approach:

$$R_\lambda = \frac{\pi L_\lambda d^2}{E_{sun_\lambda} * \cos(\theta)} \qquad (1)$$

where R_λ is top of the atmosphere reflectance, L_λ is at-satellite radiance, d is the earth-sun distance in astronomical units at the time of image acquisition, E_{sun} is mean solar exoatmospheric irradiance in each band, and θ is the solar zenith angle. E_{sun} values were determined individually for each sensor using published values.

Following the conversion to at satellite-reflectance, the modified black-body subtraction method developed by Chavez (1988) was used to perform a simple atmospheric correction to each image as detailed information on the state of the local atmosphere was not available. For ASTER and Landsat the average reflectance from a 3x3 pixel box in high altitude Lake Bujuku were used to determine the correction for the shortest wavelength band, while corrections for the remaining bands were calculated based on a power law scattering model. For the SPOT image, the reflectance from the smaller Lac du Speke was used due to haze over Lake Bujuku at the time of image acquisition. For Landsat images a clear sky scattering model was employed (λ^{-3}), for ASTER a very clear model (λ^{-4}) and for SPOT, that had extensive clouds, a hazy model (λ^{-1}) was used.

Normalized Snow Difference Index

Following the atmospheric correction, the Normalized Snow Difference Index (NDSI) was computed for each image in the following manner (Hall et al., 1995) using appropriate bands for each sensor:

$$\text{NDSI} = \frac{(\text{Band A -Band B})}{(\text{Band A +Band B})} \qquad (2)$$

The bands representing Bands A and B for each sensor are listed in Table 2

Table 2. Bands used for computing the NDSI..

Sensor	Band A	Band B
Landsat	2 (0.52-0.60 μm)	5 (1.55-1.75 μm)
ASTER	2 (0.63-0.69 μm)	4 (1.600-1.700 μm)
SPOT	2 (0.617-0.687 μm)	4 (1.580-1.750 μm)

Due in part to the larger atmospheric influences in Band 1 of ASTER and SPOT, Band 2 from both of these instruments was used to compute the NDSI, rather than a shorter wavelength band that corresponded slightly better to Band 2 of Landsat.

Thresholds were then selected to create a binary snow/ice map from each NDSI image. The selected thresholds were based on a thorough visual analysis of each image including comparisons of the binary snow maps with the original satellite images, our experience in other tropical mountain ranges and in the case of Landsat, extensive testing of the approach for snow mapping (Hall et al., 1995; Klein et al., 1998). The following thresholds were selected: 0.40 for Landsat and 0.10 for both ASTER and SPOT. To ascertain the impact of the selected threshold, additional snow maps were also created by adjusting the threshold by 0.1 NDSI units above and below the selected NDSI.

A mask was then created by buffering the 1906 glacier extents by 50 m. This mask was applied to each snow map to remove erroneously mapped snow falling well outside the glacier boundaries. For some image dates, some snow that did exist outside the buffered area may have been removed. In addition, for the 2003-12-17 Landsat image clouds that were erroneously classified as snow by the NDSI method were removed manually. The manual removal was conservative and snow totals on Mt. Baker for this date may include some cloud cover pixels.

Visual Mapping

For the three dates with minimal snow cover, visual mapping of the glaciers of the Rwenzori was also undertaken in a manner analogous to that used to map glaciers on Puncak Jaya in Papua, formerly Irian Jaya (Klein and Kincaid, 2006). False color composites were created for the 1987 Landsat, 2005 ASTER and 2006 SPOT images from the following mid-infrared, near-infrared and visible bands: Landsat 5, 4 and 2, ASTER 4, 3 and 2 and SPOT 4, 3 and 2.

The glaciers on the three main peaks comprising the Rwenzori were then mapped. Group discussions of problematic areas resulted in the following process to produce the final maps. The visual mapping was done in time sequential order and in some instances glacier extents from a previous or subsequent image were used to help constrain the mapping. Following completion of the mapping, small shifts were applied to the mapped polygons to bring the borders into alignment with the boundaries mapped on the 2006 SPOT image for consistency. In order to place overly conservative estimates of the error of our glacier mapping, the digitized glacier boundaries were contracted and expanded by 15 m using a buffering operation within a Geographic Information System (GIS). The areas of these shrunken and enlarged glacier extents are also listed in Table 3.

RESULTS AND DISCUSSION

The computed glacier areas for the three glaciated peaks in the Rwenzori are listed in Table 3 as are the areas from Taylor *et al.* (2006) for all images studied. It is apparent that substantial glacier retreat has occurred between the late 1980s and early 2000s in the Rwenzori. However, successfully quantifying this retreat using the existing satellite image archive is problematic. These problems are evident in the large differences between the mapped areas for the same images between this study and Taylor *et al.* (2006). Slight differences in glacier areas are also found between mapping methods.

Snow Cover Problems

Unfortunately, with optical images it is difficult, if not impossible, to distinguish between a pixel covered with transient snow and one containing snow or ice on a glacier surface. As is evident in Figure 4, three of the Landsat images in the time series (January 17, 1995, January 31, 2003 and December 17, 2003) all contain significant snow cover off of the glaciers. These images are not suitable for analysis of glacier areas. However, images from two of these dates from January 17, 1995 and January 31, 2003 were used by Taylor *et al.* (2006) to determine glacier extents and are thus included in Table 3 although not used in our own analysis. While it is possible to use these images to qualitatively infer glacier retreat of some of the main glaciers, given the extensive snow cover existing off of the glaciers, the published glacier areas of Taylor *et al.* (2006) for these two dates are highly suspect.

Comparisons with Previously Published Studies

As is evident in Table 4, there are large differences in the computed glacier areas for the individual peaks between our analysis and the published glacier areas from Taylor *et al.* (2006). Given the limited detail on the processing methods provided by Taylor *et al.* (2006) it is difficult to assess the origin of these large differences. Nevertheless, there are large differences in areas even though both studies employed one common mapping method – the Normalized Snow Difference Index (NDSI).

Overall, the agreement between the Taylor *et al.* (2006) and our own analysis for the 1987 Landsat image is closer than for the later Landsat dates where snow cover is more extensive. The smaller ice area on Mt. Baker (0.147 km^2) and the larger ice area on Mt. Stanley indicated by our NDSI methods are not within their stated error bounds (Table 3). Again the source of this discrepancy is unknown.

For the 1995 and 2003 Landsat images, the NDSI estimated areas of Taylor *et al.* (2006) for Mt. Speke and Mt. Stanley, as well as for the total glacier areas for the Rwenzori, are considerably less than our own best estimates. For example, the total glacier areas for the Rwenzori determined by Taylor *et al.* (2006) are much smaller than our own, 0.822 km^2 (35%) and 1.194 km^2 (55%) for the 1995 and 2003 Landsat images both groups analyzed.

With the exception of some snow covered pixels possibly falling outside of the 1906 glacier boundaries, the total areas of this study include all pixels with NDSI values > 0.40. For Taylor *et al.* (2006) to arrive at glacier areas considerably smaller than our own would require masking of a considerable portion of the snow-covered pixels or use of a considerably more restrictive NDSI threshold then the one we employed. Given the large differences in snow-covered areas using the same technique, caution should be given to any glacier areas derived from 1995 and 2003 Landsat images.

Our analysis of glaciers in the 2005 ASTER satellite image agree quite well with the published areas for these glaciers by Molg *et al.* (2006) who mapped glaciers from the same ASTER image using a combination of visible bands. The published areas, Mt. Baker 0.04±0.01, Mt. Speke 0.30±0.03 and Mt. Stanley 0.80±0.06, are in general, slightly larger on the order of 0.05 km^2 for each peak than our own (Table 3). The comparability of mapped areas gives us confidence in our own mapped areas for other dates.

Visual Mapping

Of the four image dates, only three were considered minimally contaminated with snow to accurately map glacier boundaries. From these three images: Landsat 1987-08-07, ASTER 2005-02-21 and SPOT 2006-02-10 glacier extent was mapped visually (Table 3). The 2006 ASTER image was not mapped because it was felt the 2006 SPOT image was of higher quality and little would be gained by digitizing both images for 2006. The visually mapped glacier extents are illustrated in Figure 5. The marked retreat of the glaciers from 1987 to 2005 is evident.

Comparing our visual mapping and our best estimates of glacier area for the same dates using the Normalized Difference Snow Index, we can see that overall the areas are quite comparable. In all but the glacier area mapped for Mt. Baker from the 2006 SPOT image, the visually mapped areas are all slightly higher than our best estimates from NDSI. A major source of the differences is that areas of high shadow are included in the visual maps but the NDSI values are too low for the pixels to be mapped as snow using this method. This highlights the necessity of using different methods to assess glacier areas in areas of complex topography and heavy shadows.

In order to identify potential problem areas with our visual mapping, our 1987 mapping was also compared to the 1990 glacier extent maps from Kaser and Osmaston (2002) as is illustrated in Figure 6. This comparison yields some interesting results. The first is that if snow/ice covered pixels in the Landsat image do represent only pixels containing glacier ice, then considerable retreat occurred between 1987 and 1990 on all peaks, especially on Mt. Stanley.

However, an alternative, and likely hypothesis, is that some of the snow covered pixels in the 1987 Landsat image represent snow in areas outside the glacier. To examine this we further compared our visually mapped 1987 glacier extents to the reanalyzed 1955 extents from Kaser and Osmaston (2002). Despite some geolocation errors, it is clear that the 1987 image contains snow covered pixels that lie outside the 1955 glacier boundaries. For Mt. Baker and Mt. Speke, the total areas are under 0.1 km^2: 0.049 km^2 and 0.072 km^2, for Mt. Baker and Mt. Speke, respectively. However, for Mt. Stanley, the area mapped as snow/ice in 1987, but not as glacier in 1955 is 0.335 km^2. This would indicate that quite possibly our estimated glacier area for Mt. Stanley in 1987 is too large.

It is also interesting to note that on all peaks, but primarily Mt. Stanley and Mt. Speke there are considerable areas mapped as glacier in 1990, but not in 1987. In some areas such as the eastern slopes of Mt. Stanley, it is clear that areas mapped as containing glacier in 1990 clearly did not contain snow or ice in 1987 and may indicate problems in the mapped 1990 extents. The same is true for Mt. Speke. In addition, there exists several small ice areas that while mapped as glaciers in both 1987 and 1990 are offset geographically.

Table 3. Glacier areas computed for the individual peaks of the Rwenzori.

	NDSI[1]			**Visual Mapping[2]**			**Taylor[3]**	
	–0.1	**Center**	**+0.1**	**–15m**	**Mapped**	**+15m**	**Supervised**	**NDSI**
1987-08-07 – Landsat								
Mt. Baker	0.253	0.233	0.206	0.172	0.273	0.388	0.43±0.13	0.38±.04
Mt. Speke	0.687	0.644	0.588	0.587	0.770	0.968	0.65±0.18	0.63±.0.2
Mt. Stanley	1.249	1.201	1.134	1.334	1.511	1.834	1.03±0.25	1.00±0.05
Total	2.189	2.081	1.928	2.093	2.554	3.19	2.11±0.56	2.01±0.11
1995-01-17 – Landsat								
Mt. Baker	0.198	0.159	0.125				0.21±0.06	0.20±0.09
Mt. Speke	1.161	0.989	0.755				0.45±0.11	0.44±0.17
Mt. Stanley	1.358	1.174	0.986				0.69±0.15	0.86±0.10
Total	2.717	2.322	1.8666				1.35±0.32	1.50±0.36
2003-01-31 – Landsat								
Mt. Baker	0.156	0.128	0.102				0.16±0.05	0.11±0.03
Mt. Speke	0.893	0.812	0.678				0.40±0.09	0.35±0.11
Mt. Stanley	1.321	1.214	1.103				0.53±0.09	0.50±0.20
Total	2.370	2.154	1.883				1.09±0.22	0.96±0.34
2003-12-17 – Landsat								
Mt. Baker	0.038	0.017	0.008					
Mt. Speke	1.326	1.1211	1.053					
Mt. Stanley	1.818	1.723	1.578					
Total	3.182	2.951	2.639					
2005-02-21 – ASTER								
Mt. Baker	0.035	0.027	0.018	0.014	0.033	0.058		
Mt. Speke	0.261	0.208	0.173	0.147	0.231	0.330		
Mt. Stanley	0.762	0.694	0.625	0.547	0.725	0.922		
Total	1.058	0.929	0.816	0.708	0.989	1.31		
2006-02-10 – SPOT								
Mt. Baker	0.043	0.034	0.022	0.015	0.030	0.052		
Mt. Speke	0.273	0.191	0.123	0.139	0.222	0.320		
Mt. Stanley	0.858	.0689	0.558	0.521	0.723	0.936		
Total	1.174	0.914	0.703	0.675	0.975	1.308		
2006-09-04 – ASTER								
Mt. Baker	0.086	0.056	0.044					
Mt. Speke	0.450	0.335	0.261					
Mt. Stanley	0.819	0.748	0.678					
Total	1.355	1.139	0.983					

[1]NDSI center values vary by sensor. The NDSI used to compute the center value for Landsat is 0.4, for ASTER and for SPOT, while the -0.1 and +0.1 columns represent the areas computed for NDSI values decreased and increased by 0.1 NDSI values for each sensor, respectively

[2]For the visual mapping the mapped column represents the area for the mapped boundaries. The -15m and +15m represent the areas in which the entire boundary has been eroded and dilated by 15 m, respectively.

[3]Values from Taylor *et al.* (2006) Table 1.

Geolocation errors are the cause of several of the observed differences. Such geolocation errors and problems in combining satellite-based glacier maps with ground based maps has been noted in other locations (e.g., Klein and Kincaid, 2006). These problems also point to the desirability of orthorectification of the Landsat images to enable better comparisons. In general, this study also highlights that glacier extents mapped from sources other than satellite images may have their own problems.

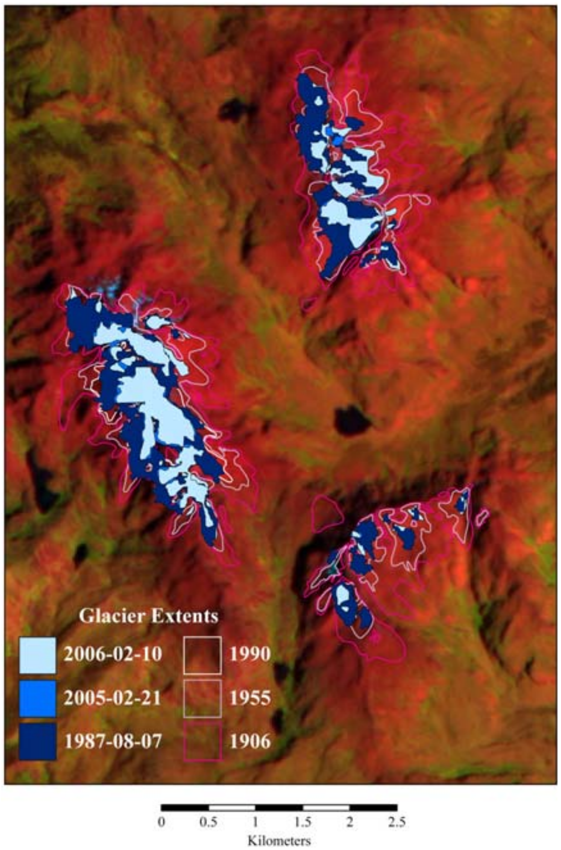

Figure 5. Glacier extents visually mapped from 1987 Landsat, 2005 ASTER and 2006 SPOT images area.

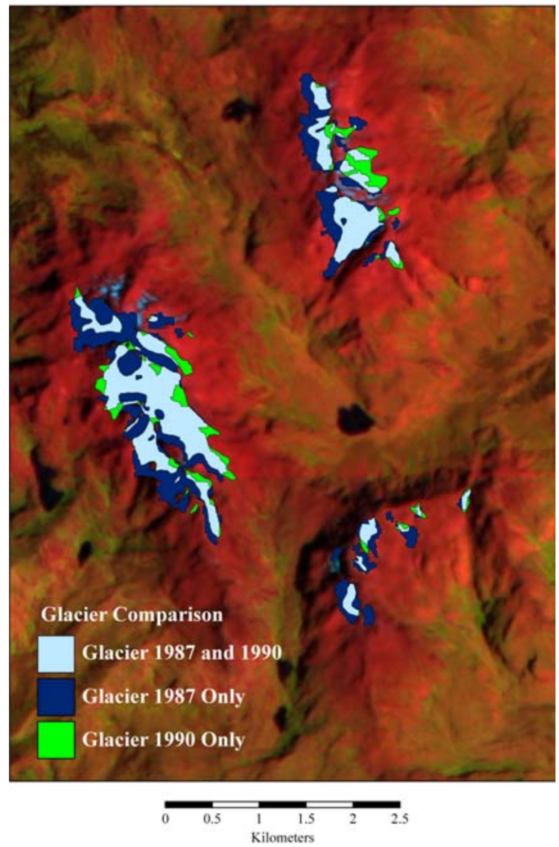

Figure 6. Comparison of our visual mapping of glacier extents in 1987 (this study) and the 1990 mapped extent (Kaser and Osmaston, 2002).

Summary of Glacier Retreat in the Rwenzori

Based on previous studies and our own analysis, our interpretation of the glacier retreat of the Rwenzori glaciers follows. Figure 7 illustrates both previously published estimates and our own areas from visual mapping. Our visual mapping may contain inaccuracies, but we feel it is the best estimate of glacier areas that can be derived from the satellite archive.

Our larger estimate of glacier extent in 1987 than Taylor *et al.* (2006) is due to our inclusion of highly shadowed areas that appear to contain ice, but whose NDSI values are too low to be classified as ice spectrally. In addition, the glacier areas indicated by any remote sensing method in 1987 may be incorrect due to snow cover existing on non-glacier surfaces, especially on Mt. Stanley. The apparent large decrease in total glacier area between 1987 and 1990 can thus be due to an overestimated glacier area in 1987 and, possibly, with problems in the reanalyzed 1990 mapping as well.

The Taylor *et al.* (2006) glacier areas for 1995 and 2003 cannot be considered reliable as it is obvious that snow cover exists off of the glaciers themselves. Our own analysis of these images shows the actual are of snow ice is much larger than the areas published by Taylor *et al.* In addition, it would appear based on the 2005 and 2006 images, that the Taylor *et al.* (2006) estimates for Mt. Stanley are smaller than the areas measured in 2005 and again in 2006.

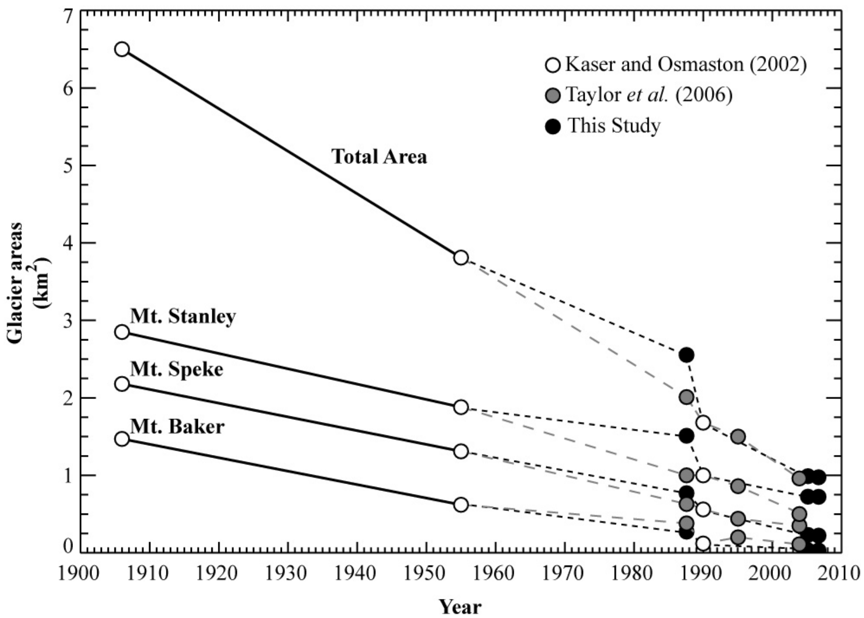

Figure 7. Retreat of the Rwenzori Glaciers with previously published information from Kaser and Osmaston (2002) [white circles] and Taylor *et al.* (2006) [gray circles]. Our own estimates from visual mapping are shown as black circles.

CONCLUSIONS

From 1987 to 2005, considerable glacier retreat is evident in the Rwenzori Range in eastern Africa based on satellite images. However, quantifying this retreat is difficult given that few cloud-free images exist and some of those are severely impacted by cloud cover. We reiterate the conclusion of Mölg *et al.* (2006) that the Taylor *et al.* (2006) analysis does not meet the accuracy requirements for glacier mapping in the tropics.

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